

Comparative Strength Performance of Stone and Asphalt Wearing Courses for Low-Speed Urban Roads

Derick Elvis Kamala,

Institute of Technology, Bandung, Indonesia.

Email: kamaladerick@yahoo.com

Abstract:

Conventional asphalt wearing courses remain the dominant surface material for urban roads; however, their performance is often compromised in low-speed environments characterized by frequent braking, concentrated loading, and moisture exposure. Under such conditions, asphalt surfaces are susceptible to rutting, stripping, and strength degradation, prompting renewed interest in alternative surfacing materials with higher mechanical durability. This study presents a comparative evaluation of the strength performance of stone and asphalt wearing courses using laboratory-based mechanical indicators. The objective is to assess the relative suitability of both materials as wearing course layers based on their resistance to crushing, impact, abrasion, and tensile loading. Stone strength performance was evaluated using Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests under both dry and wet conditions, together with the Los Angeles Abrasion test to assess durability. Asphalt wearing course performance was assessed through Marshall Stability, Indirect Tensile Strength (ITS), and Unconfined Compressive Strength (UCS) tests, representing load-bearing capacity, tensile resistance, and compressive behavior, respectively. All tests were conducted following relevant international standards to ensure consistency and comparability. The results indicate that stone exhibits superior resistance to impact, crushing, and abrasion, particularly under dry conditions, reflecting its strong compressive-dominated mechanical behavior. Asphalt demonstrates higher tensile strength and better resistance to crack initiation, attributable to its viscoelastic binder-controlled response. Moisture exposure was found to reduce strength indicators for both materials, with a more pronounced effect observed in asphalt mixtures. From an engineering perspective, stone wearing courses are more suitable for low-speed urban roads, intersections, and braking zones where compressive and abrasion stresses dominate, while asphalt wearing courses remain preferable for applications requiring higher tensile resistance and riding comfort.

Keywords: Asphalt, Stone, Laboratory Tests, Strength Testing, Stone and Asphalt Wearing Courses, Intersubjectivity.

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1. INTRODUCTION

The wearing course is the uppermost pavement layer directly exposed to traffic loading and environmental actions, and its performance strongly influences safety, durability, and long-term serviceability of road infrastructure (Huang, 2004; El-Korchi & Mallick, 2018). Conventional asphalt wearing courses dominate modern urban road networks due to their constructability, smooth riding quality, and well-established design methods (Roberts et al., 1996; Asphalt Institute, 2014). Despite these advantages, asphalt surfaces remain vulnerable to distress mechanisms such as rutting, cracking, ravelling, and moisture-induced damage, particularly in low-speed environments where braking, turning, and channelised traffic produce high contact stresses and repeated shear loading (Zhou et al., 2019; Zhang et al., 2020).

In urban intersections, bus bays, parking areas, and hilly road sections, asphalt wearing courses often experience premature deterioration. Frequent braking and slow-moving heavy vehicles concentrate compressive and shear stresses within the surface layer, accelerating permanent deformation and reducing structural capacity (Zhou et al., 2019). Moisture exposure further exacerbates these issues by weakening the aggregate binder bond, increasing susceptibility to stripping and strength loss (Zhang et al., 2020). These limitations have motivated renewed interest in alternative wearing course materials that can better resist compressive loading, abrasion, and surface damage under demanding service conditions (World Bank, 2019).

Stone wearing courses, particularly cobblestone-type pavements, represent a historically proven surfacing system that has demonstrated long-term durability under traffic loading (Stone Federation Great Britain, 2019; Knapton, 2016). Stone pavements function as rigid, interlocking units in which load transfer occurs through direct stone-to-stone contact rather than through a continuous binder. Their mechanical performance is governed primarily by intrinsic rock properties, including resistance to crushing, impact, and abrasion (Majer et al., 2024). As a result, stone wearing courses typically exhibit high resistance to deformation, surface wear, and polishing, making them well suited to environments dominated by compressive and abrasion-related stresses.

Although stone pavements have been widely applied in historic urban streets and traffic-calmed zones, their engineering evaluation has often remained qualitative or descriptive (Stone Federation Great Britain, 2019). In contrast, asphalt wearing courses are extensively characterised through standardized laboratory tests that quantify load-bearing capacity, tensile resistance, and deformation behaviour (Brown et al., 2001; Asphalt Institute, 2014). This imbalance has contributed to a lack of rigorous, side-by-side comparison between stone and asphalt wearing courses using measurable strength-related indicators. Consequently, decision-making regarding the selection of stone as an alternative wearing course material is frequently based on empirical experience rather than objective performance data (Babashamsi et al., 2016; Jung et al., 2022).

Comparing stone and asphalt wearing courses presents inherent challenges because the two materials exhibit fundamentally different mechanical behaviours. Stone pavements act as modular, compression-dominated systems, while asphalt behaves as a viscoelastic continuum whose response is strongly influenced by temperature and loading rate

(Huang, 2004; Roberts et al., 1996). Meaningful comparison therefore requires the selection of strength parameters that reflect equivalent engineering behaviours rather than identical test methods. Aggregate Crushing Value, Aggregate Impact Value, and Los Angeles Abrasion tests provide suitable indicators of stone resistance to compressive loading, impact forces, and long-term wear. For asphalt wearing courses, Marshall Stability, Indirect Tensile Strength, and Unconfined Compressive Strength tests represent established measures of load-carrying capacity, tensile resistance, and compressive performance (Brown et al., 2001; Asphalt Institute, 2014).

Despite the availability of these standardized tests, limited research has integrated them within a unified framework to compare the strength performance of stone and asphalt wearing courses. Most previous studies focus on material-specific performance or life-cycle considerations without directly addressing relative mechanical suitability under similar service conditions (Babashamsi et al., 2016; Jung et al., 2022). This gap is particularly relevant for low-speed urban roads, where pavement performance is governed more by strength, durability, and resistance to localized damage than by ride comfort alone (World Bank, 2019).

The objective of this study is to conduct a comparative evaluation of the strength performance of stone and asphalt wearing courses using laboratory-based mechanical indicators. By systematically assessing crushing, impact, abrasion, tensile, and compressive resistance, the study aims to provide an objective engineering basis for material selection under conditions where conventional asphalt wearing courses are prone to premature distress. The findings are intended to support performance-based decisions regarding the appropriate use of stone and asphalt wearing courses in urban road applications

1.2 Stone wearing course revival

Stone wearing courses are increasingly being reconsidered for modern road applications, particularly in low-speed, high-stress environments where conventional asphalt surfaces are prone to premature deterioration (World Bank, 2019; Majer et al., 2024). Such conditions include urban intersections, bus bays, parking areas, and steep road sections characterized by frequent braking, turning, and concentrated wheel loads. In these settings, pavement performance is governed primarily by resistance to compressive stress, abrasion, and surface damage rather than by ride comfort alone (Knapton, 2016).

The primary advantage of stone wearing courses lies in their high compressive resistance and mechanical durability. Stone pavements function as rigid, interlocking units that transfer loads through direct stone-to-stone contact, minimizing permanent deformation under sustained loading (Stone Federation Great Britain, 2019). Their inherent resistance to crushing, impact, and abrasion enables them to maintain structural integrity and surface texture over extended service periods (Majer et al., 2024). Unlike binder-dependent materials, stone surfaces are less sensitive to temperature variations and exhibit stable performance under repeated loading. These characteristics make stone wearing courses particularly suitable for applications where durability, strength, and resistance to localized distress are critical performance requirements (World Bank, 2019).

1.3 Literature review

Existing literature evaluates the strength performance of stone and asphalt wearing courses using different but well-established mechanical indicators (Babashamsi et al., 2016; Jung et al., 2022). For stone materials, Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), and Los Angeles Abrasion tests are commonly used to assess resistance to compressive loading, impact forces, and long-term abrasion, which govern durability in high-stress surface applications (Majer et al., 2024; Stone Federation Great Britain, 2019). Asphalt wearing course performance, in contrast, is typically characterized through Marshall Stability, Indirect Tensile Strength (ITS), and Unconfined Compressive Strength (UCS), reflecting load-bearing capacity, tensile resistance, and compressive behavior of the mixture (Brown et al., 2001; Asphalt Institute, 2014). These indicators capture the fundamentally different mechanical responses of rigid stone systems and viscoelastic asphalt layers (Huang, 2004; El-Korchi & Mallick, 2018). However, most studies assess these materials independently using material-specific tests without establishing equivalent performance measures (Babashamsi et al., 2016; Jung et al., 2022). As a result, there is a lack of direct, quantitative comparison between stone and asphalt wearing courses based on unified strength-related criteria (Jung et al., 2022; Majer et al., 2024).

1.4 Research gap

Existing studies evaluate stone and asphalt independently, with limited comparative assessment using unified strength indicators.

1.5 Objective

- I. To evaluate and compare the strength performance of stone and asphalt wearing courses using laboratory-based mechanical indicators representing compressive, impact, abrasion, tensile, and unconfined compressive behavior.
- II. To establish an engineering basis for selecting appropriate wearing course materials in low-speed, high-stress road environments based on comparative strength-related performance.

2. MATERIALS AND METHODS

2.1 Materials

The stone material used in this study consists of naturally occurring cobblestone units derived from hard igneous and metamorphic rock formations, selected for their high mechanical strength and durability (Stone Federation Great Britain, 2019; Majer et al., 2024). The stones were manually processed to obtain representative samples suitable for laboratory evaluation. Material selection was based on typical properties required for wearing course applications, including resistance to crushing, impact, and abrasion (Knapton, 2016). The stone samples are representative of commonly used materials in

low-speed urban road applications and were prepared in accordance with standard aggregate testing requirements prior to laboratory testing (Construction Materials Laboratory (CML)).

The asphalt material evaluated in this study is a conventional Asphalt Concrete Wearing Course (AC-WC) mixture produced using penetration grade 60/70 bitumen (Asphalt Institute, 2014; Roberts et al., 1996). The mixture was obtained from a certified hot mix asphalt plant and reflects standard production practices for surface layers. The AC-WC mix was designed to meet typical wearing course specifications, providing adequate load-carrying capacity, tensile resistance, and compressive strength (Brown et al., 2001). Representative asphalt samples were collected and prepared following standard procedures to ensure consistency for Marshall Stability, Indirect Tensile Strength, and Unconfined Compressive Strength testing (Construction Materials Laboratory (CML)).

2.2 Laboratory tests for stone

The strength performance of the stone wearing course material was evaluated using standardized aggregate tests that quantify resistance to crushing, impact, and abrasion. All tests were conducted in accordance with relevant British and ASTM standards and following the standard procedures outlined in the Construction Materials Laboratory (CML) Manual for Aggregate Testing, Faculty of Civil and Environmental Engineering (Construction Materials Laboratory (CML)).

Aggregate Crushing Value (ACV) testing was performed to evaluate resistance to gradual compressive loading. The test procedure followed BS 812-110, with sample preparation, oven-drying, sieve analysis, and loading sequence conducted in accordance with *CML Manual – Part A: Aggregate Strength Tests, Section on Crushing Value Test (ACV)* (Construction Materials Laboratory (CML)). Tests were carried out under both dry and wet conditions to account for moisture influence on compressive resistance.

Aggregate Impact Value (AIV) testing was used to assess the toughness of the stone material under sudden impact loading representative of braking and dynamic traffic actions. The test followed BS 812-112, while sample conditioning, impact application, and fines measurement procedures were conducted in accordance with *CML Manual – Part A: Aggregate Strength Tests, Section on Impact Value Test (AIV)* (Construction Materials Laboratory (CML)). Both dry and moisture-conditioned samples were tested.

Los Angeles Abrasion (LA Abrasion) testing was conducted to evaluate abrasion resistance and long-term durability of the stone material under repeated impact and wear. The test was performed in accordance with ASTM C131, using standardized drum rotation, abrasive charge, and mass-loss determination. Sample preparation, rotation control, and post-test sieving followed *CML Manual – Part B: Aggregate Durability Tests, Section on Abrasion Resistance (Los Angeles Test)* (Construction Materials Laboratory (CML)).

2.3 Laboratory tests for asphalt

The strength performance of the asphalt wearing course material was evaluated using standardized laboratory tests that represent load-bearing capacity, tensile resistance, and compressive behaviour of asphalt mixtures. All tests were conducted in accordance with relevant ASTM and BS standards and strictly following the procedures specified in the Construction Materials Laboratory (CML) Manual, Faculty of Civil and Environmental Engineering (Construction Materials Laboratory (CML); Asphalt Institute, 2014).

2.3.1 Marshall stability and flow test

Marshall Stability and Flow testing was conducted to assess the load-carrying capacity and deformation characteristics of the asphalt wearing course mixture. The test procedure complied with ASTM D6927 and BS 598-107. Specimen preparation, compaction using the Marshall hammer, conditioning temperature, and loading rate were carried out in accordance with *CML Manual – Part C: Asphalt Mix Design and Marshall Testing, Section C-1: Marshall Stability and Flow Test* (Construction Materials Laboratory (CML); Asphalt Institute, 2014). Cylindrical specimens were compacted to standard dimensions to ensure uniform density and air-void distribution.

2.3.2 Indirect tensile strength (ITS) test

The Indirect Tensile Strength test was used to evaluate the tensile resistance and cracking potential of the asphalt mixture. Testing followed ASTM D6931 and BS EN 12697-23. Sample conditioning, loading configuration, and tensile strength determination were conducted according to *CML Manual – Part D: Asphalt Mechanical Properties, Section D-1: Indirect Tensile Strength (ITS) Test* (Construction Materials Laboratory (CML); Brown et al., 2001). Specimens were conditioned at the specified test temperature prior to loading to ensure consistent test conditions.

2.3.3 Unconfined compressive strength (UCS) test

Unconfined Compressive Strength testing was performed to determine the axial compressive strength of the asphalt mixture without lateral confinement. The test was conducted in accordance with ASTM D1074. Specimen dimensions, loading rate, axial stress application, and failure criteria followed *CML Manual – Part D: Asphalt Mechanical Properties, Section D-2: Unconfined Compressive Strength (UCS) Test* (Construction Materials Laboratory (CML); Brown et al., 2001). UCS values were calculated from the maximum axial stress recorded at failure. All asphalt laboratory tests were carried out following CML requirements for specimen preparation, temperature control, equipment calibration, and systematic data recording to ensure repeatability and reliability of results (Construction Materials Laboratory (CML)).

2.4 Data processing and comparative framework

Data processing was carried out by normalizing laboratory strength results into comparative, dimensionless indices to enable evaluation of stone and asphalt wearing courses tested using different mechanical methods. Strength indicators for stone, including Aggregate Crushing Value, Aggregate Impact Value, and Los Angeles Abrasion, were treated as inverse performance measures, where lower values indicate higher resistance to compressive loading, impact, and abrasion.

Asphalt strength indicators, including Marshall Stability, Indirect Tensile Strength, and Unconfined Compressive Strength, were treated as direct measures of performance, where higher values represent greater load-bearing, tensile, and compressive capacity. Normalization preserved the physical significance of each test while allowing cross-material comparison within a unified framework. This approach is justified because stone and asphalt resist traffic loading through different dominant mechanisms, with stone performance governed primarily by compressive and abrasion resistance and asphalt performance governed by tensile and viscoelastic behavior. Comparing equivalent strength modes rather than identical test outputs provides an engineering-relevant basis for assessing material suitability under similar service conditions.

3. RESULTS

3.1 Stone strength results

Test	Condition	Mean Value (%)	Typical Acceptable Limit (%)	Performance Classification
Aggregate Crushing Value (ACV)	Unsoaked (Dry)	20.7	≤ 30	Good
Aggregate Crushing Value (ACV)	Soaked (Wet)	23.1	≤ 30	Good
Aggregate Impact Value (AIV)	Unsoaked (Dry)	22.7	≤ 30	Good
Aggregate Impact Value (AIV)	Soaked (Wet)	35.9	≤ 30	Poor
Los Angeles Abrasion (LA)	Dry	25.4	≤ 30	Good

Table 1: Stone strength Results and their Limit

3.2 Asphalt strength results

Test	Mean Result	Unit	Typical Requirement / Limit	Compliance
Marshall Stability	17.0	kN	≥ 9.0 kN (AC Wearing Course – Marshall method, CML adopted practice)	Complies
Marshall Flow	2.7	mm	2.0 – 4.0 mm (Marshall practice)	Complies
Indirect Tensile Strength (ITS)	0.45	MPa	≥ 0.40 MPa (typical acceptability for AC wearing course)	Complies
Unconfined Compressive Strength (UCS)	0.52	MPa	No fixed limit (used as comparative indicator)	Reasonable

Table 2: Asphalt Strength Results with their Limitation

3.3 Calculation of indices

3.3.1 Indices for stone tests (ACV, AIV, LA)

Taking into mind that for Stones the lower values = better performance:

$$I = \frac{\text{Limiting Value}}{\text{Measured Value}} \quad \text{Equation 1}$$

Where by:

Limit value = **30%** (adopted for ACV, AIV, LA) as per CML

3.3.2 For Asphalt tests (Marshall, ITS, UCS)

Taking into mind that for Asphalt the higher values = better performance

$$I = \frac{\text{Measured Value}}{\text{Required (reference) Value}} \quad \text{Equation 2}$$

Where by:

- $M_{\text{req}}=15\text{kN}$
- $\text{ITS}_{\text{req}}=0.40\text{MPa}$
- $\text{UCS}_{\text{req}}=0.50\text{MPa}$

4.8.2.1 Stone (Dry / Unsoaked) – Index Calculations

Given values

- $\text{ACV} = 20.7 \%$
- $\text{AIV} = 22.7 \%$
- $\text{LA} = 25.4 \%$

Crushing Resistance Index (ACV)

$$\text{IACV} = 20.7 / 30 = 1.449$$

Impact Resistance Index (AIV)

$$\text{IAIV} = 22.7 / 30 = 1.322$$

Abrasion Resistance Index (LA)

$$LA = 25.4 / 30 = 1.181$$

3.4. Asphalt – index calculations

Given values

- Marshall Stability = 17.0 kN
- ITS = 0.45 MPa
- UCS = 0.52 MPa

Marshall Stability Index

$$I_M = 15.0 / 17.0 = 1.133$$

ITS Index

$$I_{ITS} = 0.40 / 0.45 = 1.125$$

UCS Index

$$I_{UCS} = 0.50 / 0.52 = 1.040$$

Strength Index	Stone (Dry)	Stone (Wet)	Asphalt
Crushing Resistance Index	1.449	1.299	1.133
Impact Resistance Index	1.322	0.836	1.125
Abrasion Resistance Index	1.181	1.181	1.040

Table 3: Showing the Strength Index for Stone and Asphalt

TABLE SHOWS THE INDICES results for Stones and Asphalt

The distribution of the normalized performance indices across the evaluated stress modes is illustrated in Figure 1.

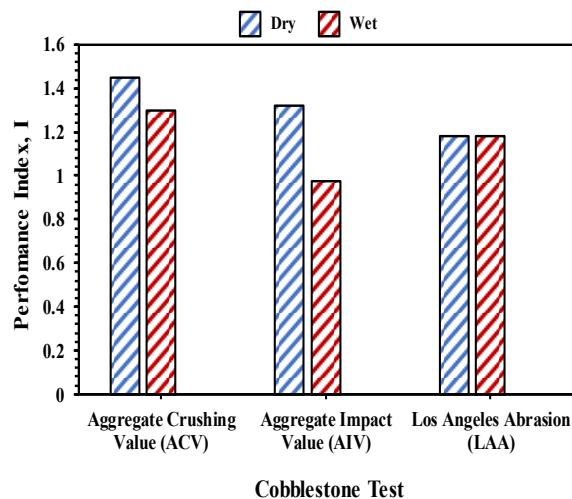


Figure 1 Normalized Performance of Cobblestone Tests

The normalized mechanical performance indices for the asphalt concrete mixture are illustrated in Figure 2.

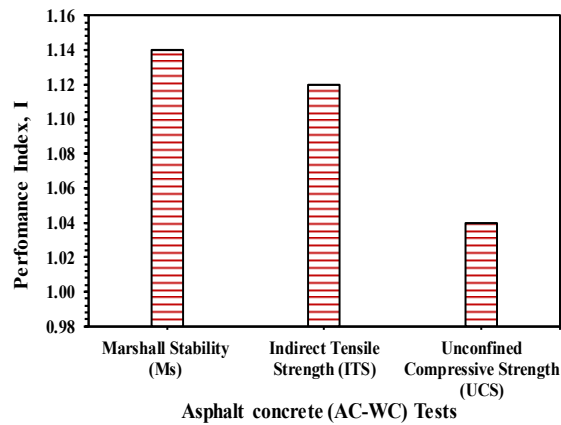


Figure 2 Normalized performance of Asphalt Concrete Tests

3.5 Comparative strength index

With equal Weight

$$\omega_1 = \omega_2 = \omega_3 = \frac{1}{3} \quad \text{Equation 3}$$

$$SI = \frac{I_1 + I_2 + I_3}{3} \quad \text{Equation 4}$$

Each test result was converted into a dimensionless normalized index by relating the measured value to its corresponding limit or requirement. For aggregate tests, lower values indicate better performance, while for asphalt tests, higher values indicate better performance; therefore, all indices were formulated such that higher index values represent superior material strength.”

Then by considering the equation above and using the normalized indices (higher = better):

Material / Condition	Indices Used	Composite SI
Stone (Dry / Unsoaked)	(1.449, 1.322, 1.181)	1.317
Stone (Wet / Soaked)	(1.299, 0.836, 1.181)	1.105
Asphalt	(1.133, 1.125, 1.040)	1.099

Table 4: Showing the Index Ranking

Then, by Ranking the Composite SI

1. **Stone (Dry)** = 1.317
2. **Stone (Wet)** = 1.105
3. **Asphalt** = 1.099

The variation of the normalized indices across the evaluated mechanical stress mode is illustrated in Figure 3 below:

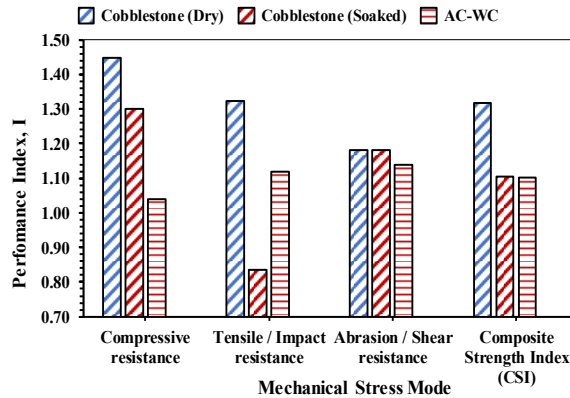


Figure 3 Mechanical stress Modes against Performance Index

4. DISCUSSION

4.1 Compression vs tension behaviour

The mechanical behaviour of stone and asphalt wearing courses differs fundamentally due to their contrasting material structures and load-transfer mechanisms. Stone wearing courses behave as rigid, modular systems in which traffic loads are transferred through direct stone-to-stone contact and interlocking. As a result, their performance is predominantly compression-dominated, with resistance governed by the intrinsic strength of the stone material. Indicators such as Aggregate Crushing Value, Aggregate Impact Value, and Los Angeles Abrasion reflect the ability of stone to withstand compressive stresses, sudden impact loads, and surface wear without undergoing permanent deformation. This behaviour makes stone wearing courses particularly effective in environments where vertical contact stresses and abrasion forces control pavement performance.

In contrast, asphalt wearing courses behave as continuous, bound layers with a tensile-dominated mechanical response. Although asphalt can sustain compressive loads, its structural integrity depends strongly on tensile resistance within the mixture, which governs crack initiation, fatigue performance, and resistance to load-induced separation. Indirect Tensile Strength and Unconfined Compressive Strength tests capture the asphalt mixture's ability to resist tensile cracking and axial stress under traffic loading. The viscoelastic nature of asphalt means that tensile stresses develop within the layer under repeated loading, braking, and temperature variations, making tensile performance a critical determinant of durability.

These distinct mechanical responses justify evaluating stone and asphalt wearing courses using different but equivalent strength modes. Comparing compression-dominated behaviour in stone with tensile-dominated behaviour in asphalt provides an engineering-relevant framework for assessing material suitability under similar service conditions.

4.2 Moisture sensitivity

Moisture exposure influences the strength performance of both stone and asphalt wearing courses, though through different mechanisms. For stone materials, the presence of water reduces effective contact and interlock between particles, leading to increased susceptibility to crushing and impact damage under load. This effect is reflected by higher AIV and ACV values under wet conditions, indicating a reduction in mechanical resistance compared with dry states. Despite this reduction, stone retains its compression-dominated behaviour and continues to provide stable structural performance in high-stress applications. In asphalt wearing courses, moisture sensitivity is primarily associated with the bitumen binder, where water weakens the aggregate–binder bond and promotes stripping and strength loss. This degradation affects tensile resistance and accelerates crack initiation under repeated loading. The differing moisture response mechanisms highlight the importance of considering environmental exposure when selecting wearing course materials for durable pavement performance.

4.3 Engineering interpretation

The comparative strength behaviour of stone and asphalt wearing courses is closely related to traffic speed, braking forces, and contact stress conditions. Low-speed traffic environments generate high contact stresses due to longer tyre–pavement interaction times, which intensify compressive and shear loading at the surface. Frequent braking and turning movements further increase localized stresses, accelerating surface deformation and material damage. Under these conditions, stone wearing courses benefit from their rigid, compression-dominated behaviour, enabling them to resist high contact stresses and abrasion with minimal permanent deformation. Asphalt wearing courses, by contrast, perform more effectively under higher-speed traffic where loads are distributed over shorter contact durations and tensile resistance governs performance. The viscoelastic nature of asphalt allows it to accommodate tensile strains but makes it more vulnerable to rutting and shear deformation in slow-moving, high-stress zones. These relationships demonstrate that material suitability depends on traffic and loading characteristics rather than material strength alone.

5. ENGINEERING IMPLICATIONS

The comparative strength behaviour of stone and asphalt wearing courses indicates that material suitability is strongly dependent on traffic operating conditions and loading characteristics. Stone wearing courses are particularly suitable for low-speed urban roads, where traffic movement is dominated by frequent stopping, braking, and turning actions. In such environments, high contact stresses and abrasion forces govern surface performance, and stone's compression-dominated behaviour provides enhanced resistance to crushing, impact, and surface wear. This makes stone wearing courses well suited for intersections and bus bays, where slow-moving heavy vehicles generate

concentrated loads and repeated braking stresses that commonly accelerate surface deterioration in flexible pavements.

Asphalt wearing courses remain more appropriate for higher-speed road sections, where traffic loads are applied over shorter contact durations and tensile resistance plays a dominant role in performance. The viscoelastic nature of asphalt allows it to accommodate tensile strains and provide smoother riding surfaces, making it suitable for comfort-oriented roads where ride quality and uniform surface texture are important. These implications highlight the importance of selecting wearing course materials based on traffic speed, loading mechanisms, and functional requirements rather than adopting a single surfacing solution for all road environments.

6. CONCLUSION

- I. Stone wearing courses exhibit superior resistance to impact and crushing stresses compared with asphalt, reflected by a higher composite strength index ($CSI \approx 1.317$) under dry conditions, confirming their compression-dominated mechanical behavior.
- II. Asphalt wearing courses demonstrate greater tensile resistance than stone, indicating improved ability to accommodate tensile strains associated with cracking mechanisms.
- III. Under abrasion- and compression-dominated conditions typical of low-speed traffic zones, stone maintains higher overall mechanical resistance than asphalt ($CSI \approx 1.102$), highlighting its durability in high-stress surface environments.
- IV. Moisture exposure reduces strength performance in both materials; however, the cobblestone CSI decreases from approximately 1.317 to 1.152, approaching asphalt performance, indicating sensitivity particularly in impact-related behavior.
- V. The comparative evaluation confirms that stone and asphalt are not interchangeable materials, as each performs optimally under different dominant strength modes governed by traffic and loading conditions.

6.1 Limitations and future work

This study is based on laboratory-scale evaluation of stone and asphalt wearing course materials using standardized strength-related tests, which may not fully capture in-service pavement behaviour under variable traffic and environmental conditions. Field validation is therefore necessary to confirm the applicability of the laboratory findings under real traffic loading, construction practices, and climatic exposure. In addition, the study does not address long-term durability and performance evolution over extended service periods, including aging, repeated loading effects, and maintenance-related influences. Future work should integrate field monitoring and long-term performance assessment to complement the laboratory-based strength evaluation.

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